THE MODE OF FORMATION OF CERTAIN GNEISSES IN THE HIGHLANDS OF NEW JERSEY—*Concluded*

CLARENCE N. FENNER
Geophysical Laboratory, Carnegie Institution of Washington

PART II. DISCUSSION OF CERTAIN THEORETICAL PRINCIPLES INVOLVED IN THE INJECTION OF THE MAGMA

It has been pointed out that the granitic magma which was intruded into the original series seems to have been of a rather thin consistency. Nevertheless the degree of fluidity could hardly have approached, even approximately, that of water or an ordinary aqueous solution. The manner in which strata have been crumpled and twisted by movements of the magma argues a very effective degree of viscosity, as does also the support seen to have been offered to thinly tabular sheets of strata standing in a nearly upright position and evidently free for considerable distances from other support than that given by the adjacent magma. On the other hand, certain phenomena indicate that magmatic fluid was absorbed by the strata with little difficulty. At first sight these properties appear quite inconsistent with each other; nevertheless it seems possible to harmonize them. In order to derive a probable explanation of this and certain other phenomena it is necessary to consider certain of the properties of magmatic solutions.

At the present time it is well recognized that the temperature of fusion of the individual minerals of a rock, or even the temperatures required to fuse the aggregate, afford no indication of the temperatures at which the magma from which the rock crystallized was liquid in the interior of the earth. Since the time of Elie de Beaumont[1] the importance of the rôle played by water and other so-called mineralizers in lowering the temperature of fusion and increasing the liquidity of magmas has been perceived; and acidic magmas are regarded, for a number of reasons, as having

[1] Elie de Beaumont, "Note sur les émanations volcaniques et métallifères," *Bull. soc. géol. fran.* (2), IV (1847), 1249–1333.

contained large amounts of water. Nevertheless the property of critical temperatures of liquids appears at times to be somewhat of an obstacle to a clear comprehension of the miscibility of rock magma with water and other volatile substances at a high temperature. The critical phenomena seem sometimes to be understood to imply that at temperatures above 374° C. water, under all circumstances, ceases to be a liquid and becomes a gas. A better statement would be that at the critical temperature and at the corresponding pressure the properties of liquid and vapor cease to differ. The discontinuity of properties which characterizes the transformation from liquid to vapor at lower temperatures and pressures disappears. Moreover, the critical temperature of a liquid is not a fixed point but varies with the amount of material in solution. With pure water the critical phenomena appear at 374° C., but when water holds material in solution the vapor pressure is lowered and the critical point is raised. The greater the amount of dissolved material the greater is the displacement.

These facts have been emphasized in an investigation recently carried out by G. W. Morey[1] in the Geophysical Laboratory, of which the results have just been published. In one experiment 2 gm. of a glass of the composition $K_2O:1.7\ SiO_2$ was heated with 4.842 gm. water to a temperature of about 360° in a gold crucible within a gas-tight steel bomb. The result was a pasty glass containing 32 per cent water. In another experiment 2 gm. of glass of the same composition as before and 5 gm. water were exposed to a temperature of 490° under the same conditions. The product obtained was a hard glass containing 20 per cent water.[2] In the latter experiment the temperature was far below that at which the dry materials would begin to melt and at the same time more than 100° above the critical temperature of water alone, and the formation of a strongly hydrated glass is a striking phenomenon.

There is, therefore, no theoretical difficulty in supposing that fused silicates may form a homogeneous solution with water and other volatile substances at high temperatures, and the properties

[1] G. W. Morey, *Jour. Amer. Chem. Soc.*, XXXVI, 2 (1914), 215-30.

[2] Evidence was obtained which showed that even those glasses which became highly rigid when cooled formed mobile liquids at the temperature of the experiments.

imparted by the presence of such volatile matter—increase of mobility and greater chemical activity—will be retained.

The ease of flow manifested by the New Jersey granite which has been described is therefore quite understandable; nevertheless it seems to have retained a quite effectual degree of viscosity, as has been pointed out in describing the field phenomena. The facility, then, with which magmatic material seems to have been transfused into the adjacent strata is not at once intelligible. The difficulties in harmonizing the phenomena which are exhibited will be better appreciated by a calculation of the rate at which a fluid under pressure enters minute pores. For instance, an approximate calculation by Poiseuille's formula shows that if we assume a liquid having a coefficient of viscosity of 1.0 (about one-tenth that of glycerine at 19° C. or 100 times greater than that of water at the same temperature) and conceive it to be pressed with a force of 810,000 gm. per square cm. (corresponding to an overhead load of about 3 km. of rock strata) against a surface of 1 sq. cm. pierced with 1,000 holes, each having a radius of 0.0001 cm., and suppose the thickness of the partition to be 1 dm., then in one year only 0.1 c.c. would ooze out on the far side.

The assumptions made are far from exact. The form and disposition of the pores in rocks do not correspond to the straight cylindrical tubes to which Poiseuille's formula closely applies, and the exact degree of viscosity is unknown, but the most important factor is the diameter of the pores, for the flow is about as the fourth power of this dimension. Thus if we had assumed pores of a radius of 0.0004 cm. (probably an excessive estimate of size for the pores of ordinary rocks under heavy load) we should have derived a value of 25 c.c. per year.

It seems, on the whole, that we can expect little movement of the magma as a unit into minute pores, and we shall have to seek an explanation of its transfusion into the adjacent rock from other considerations.

Among the phenomena shown in the field several facts merit emphasis. As I have already mentioned, the introduction of the magma seems to have been effected with remarkably little disturbance of the previously existent relations of the original layers.

It is true that the larger bodies of granite show a tendency toward a lenticular outline, indicating that in such instances the adjacent rock has been forced apart; and it is found also that flexures of a minor order have been produced in the layers, but the striking fact remains that frequently evidences of the original structure survive in the midst of large masses of granite and show little disturbance of position. The most noticeable evidence in this respect is the parallelism shown by the bands of inclusions with the regional strike of the gneisses. This is observable even in those cases where assimilation by the magma has proceeded so far that the included material no longer appears as distinct bands but merely as dark-colored *schlieren* of indefinite outline. Moreover, the presence of faint parallel lines of dark minerals within the granite alongside of inclusions, as well as a certain parallelism visible in the arrangement of the component minerals of granitic masses in which no distinct xenoliths are perceptible, implies that some sort of structural framework of solid material was retained. It cannot be supposed, therefore, that the injection of the magma was of a sudden and violent nature or that it entered by simply wedging the original rock apart along the dividing laminae and occupying the spaces made. On the contrary, it must have gained access in such a slow and quiet manner that in many places delicate structural relations were left undisturbed. In fact the process appears to have possessed many of the features of a gradual substitution rather than the violent characteristics of intrusion as we often picture them.

The advocates of *lit-par-lit* injection to whom reference has been made have supported the theory that the advance of the main body of magma was preceded by that of a more attenuated portion. They believe that these solutions in advance, which were probably similar in composition to that of the main body but characterized by the presence of a larger percentage of the volatile ingredients, exercised functions of a preparatory character, metamorphosing the material into which they penetrated and rendering it gradually more susceptible to the action of the magma which followed. Lacroix's conception[1] may be illustrated by the following quotation,

[1] A. Lacroix, "Le granite des Pyrénées et ses phénomènes de contact," *Carte géol. de France, No. 71* (1900), p. 26.

in which he describes certain contact rocks formed by the action of a granite batholith upon schists:

The characteristic of the contact phenomena of this type consists essentially in the addition of volatile or transportable materials, emanating from the magma and modifying generally in a manner more or less profound the chemical and mineralogical constitution of the sediments traversed. . . . .

In the regions which form the object of this study, and in many others, the disposition of the sedimentary beds in relation to the granite, the existence in the midst of the latter of sedimentary fragments which, in spite of their transformation, have preserved the same orientation as the peripheral schists and limestones to which they belong, finally the absence of important dislocations at the immediate contacts, tend to show that the granitic magma has been brought to its position in a slow and progressive fashion by imbibition and dissolution of the sediments for which it has been substituted.

In proportion as the granitic magma appeared in the sedimentary beds it was preceded and accompanied there by its cortège of transforming emanations, and what it had to dissolve to make place for itself was no longer normal sediments, but transfused rocks, transformed or in process of transformation by fixation of the emanations which had gone out from its own mass.

The most intense modifications undergone by the schists metamorphosed into leptynolites consist essentially in the development of a large quantity of feldspars, quartz, biotite, etc. The limit toward which these leptynolites, which are often comparable from a mineralogical standpoint with gneisses, tend is the mineralogical composition of granite itself.

In a recent article Sederholm[1] describes contact-effects of a rapakivi granite upon older hornblende-schists, with introduction of typical minerals from the rapakivi. He is able to trace out the transitional changes in the minerals of the schist by absorption of material from the granite. "Microscopically as well as macroscopically it is shown, therefore, that the whole schist-mass has been permeable for gases and juices (*Säfte*) which have gone out of the granite magma, as well as for the magma itself in further progress of change. This contact would have convinced even the most zealous anti-injectionists."

The ideas which are formulated in these quotations have met with opposition from some geologists, but the objections seem to be based partly upon a misconception. The advocates of the

[1] J. J. Sederholm, "Ueber ptygmatische Faltungen," *Neu. Jb.*, XXXVI (September, 1913), Beilage-Band, p. 491.

doctrines have evidently had in mind their application to a certain type of phenomenon and do not imply that all granitic intrusions have occurred under like conditions or been accompanied by similar effects. It seems to be considered at times that the observations of Lacroix in the Pyrenees are opposed by those of Brögger in the Christiania region, but these two geologists themselves evidently perceived that they had to do with processes of a different nature and that the same phenomena should not be sought or the same explanation applied. Lacroix[1] has discussed Brögger's views and says: "None of the arguments which this scientist deduces from the study of his region bears against the theory of assimilation, applied to the Haute-Ariège; the facts which he has described are in effect the antithesis of those which I have set forth in this memoir." He suggests that the dissimilarities may be attributed to differences in the depth at which the intrusions took place in the two regions.

Brögger[2] also states that it would not be justifiable without further evidence to apply his observations on the Christiania district to the granite regions of the older primitive rocks and regionally metamorphosed fold-mountains. Evidently both Lacroix and Brögger recognize the fact that the type of granitic intrusion to which each has devoted his attention is not the only form which is found.

The relations which Michel-Lévy, Lacroix, Sederholm, and others have described offer an array of evidence in confirmation of their views, and there seems to be no inherent obstacle to accepting them.

In trying to account for the formation of a dilute magmatic solution in advance of the main invasion several possibilities suggest themselves.

It appears probable that the escape of volatile constituents through pores of the wall-rock too minute in size to permit unchanged magma to follow would have a tendency in this direction. Field evidence appears to warrant the view that considerable quantities of vapors have often escaped in this manner and that

[1] A. Lacroix, "Le granite des Pyrénées et ses phénomènes de contact," *Carte géol. de France, No. 64* (1898), p. 63.

[2] W. C. Brögger, *Die Eruptivgesteine des Christiania-Gebietes*, II (1895), 152.

important results have been accomplished through their agency. We must suppose that these gases will exert a fluxing or solvent action upon the minerals of the walls, so that some fraction of them shall form a solution with these minerals, giving rise to a sort of secondary magma within the walls.

Moreover, during the advance of streams of magma between layers of rock, such as is characteristic of *lit-par-lit* injection, it seems almost inevitable that by contact with the cooler walls a portion of their load of dissolved material should be deposited. Thus the solutions ahead would become progressively more dilute, but with the rise of temperature ultimately produced in the walls by the stores of heat imparted to them by a number of closely adjacent streams of magmatic solution unchanged magma would finally enter among the layers and carry farther toward a conclusion the processes of transformation initiated by the solutions in advance.

By whatever means a differentiation of the magma-streams is effected, the advance of the magma into the wall-rock would be attended by phenomena of various sorts, such as impregnation of the walls, solution and removal of some of the components of the wall-rock, and reactions with the minerals with which the solution came into contact.

When the chemical nature of the wall-rock differs greatly from that of the magma the reactions between the two might be expected to effect striking results. Limestones seem especially fitted to react with the magma, but other rocks may participate in a like manner. For this reason it may not be possible to decide what the nature of the original rock has been, as was pointed out in considering the character of the strata invaded by the magma in the New Jersey example. Instances of the extreme effect produced by such reactions were found by Adams and Barlow[1] in the Haliburton-Bancroft area. A passage in their publication refers to a certain contact of a granite batholith with the limestone wall-rock, and reads as follows:

> . . . . The limestone bands fade away imperceptibly into the amphibolite, the latter being undoubtedly produced by the alteration of the limestone. These rocks are invaded by the granite, traversing them in apophyses which swarm

[1] Adams and Barlow, "Geology of the Haliburton and Bancroft Areas," *Memoir No. 6, Canadian Geological Survey* (1910), p. 101.

through them in all directions, often running parallel to the banding, and elsewhere cutting across it. . . . . The alteration is due not only to the proximity of the main mass of the batholith, but to the immense amount of granitic material which occurs intruded through the series, sometimes in large masses, but very frequently in thin bands which have found their way in between the beds of the invaded limestone, changing it into amphibolite, and presenting a typical instance of *lit-par-lit* injection. The granite, furthermore, not only penetrates this amphibolite series, but floats off masses of it, which, in the form of bands, streaks, and isolated shreds, are seen thickly scattered through the granite in the vicinity of the contact. . . . . The separate fragments of amphibolite, where completely surrounded by the granite, while clearly nothing more than masses of altered limestone, are rather harder, and have a more granitized appearance than the rock which is still interstratified with the limestone.

From the various descriptions which have been cited it appears that the type of intrusion to which the term *lit-par-lit* injection has been applied presents evidences that the invasion of the magma is preceded by the advance of a wave of metamorphism into the wall-rock, by which the character and composition of the original material are radically altered. By the deposition of magmatic minerals and by the removal in solution of certain of the previous constituents, the composition tends to approach that of the magma itself, and when blocks of wall-rock are finally engulfed in the magma their composition may be so changed that their assimilation effects but little change in the composition of the latter.

If this conception is well-grounded the zone of metamorphism which surrounds areas of *lit-par-lit* injection is not to be considered as wholly an after-effect of intrusion, due to expulsion of volatile substances during the consolidation of the magmatic mass, but also as due to a preliminary process, ultimately leading up to an invasion of the magma and assimilation of the altered material.

SUMMARY

A description has been given of the structural relations observed in a certain area of banded gneisses of pre-Cambrian age in Northern New Jersey, where unusually favorable conditions for observation have been found. The structures shown here are believed to be typical of those prevailing over considerable areas in this portion of the state. Evidence is given leading to the belief that the structures at this locality cannot well be attributed to the squeezing-out

of a partly differentiated magma or to the shearing and recrystallization of a solidified rock, but that their origin must be looked for in a process involving the injection of a thinly fluid granitic magma between the layers of an original rock of laminated structure. Structures which still survive in the larger bodies of granite indicate that the process of injection was carried out in a most quiet and gradual manner, and possessed many of the characteristics of a substitution of the original material by the magmatic solution rather than the features of a violent intrusion. The observed relations are very similar to those which French geologists have described under the name of *lit-par-lit* injection, and the mode of operation is believed to have been essentially the same.

Certain features observed in the gneisses imply properties of the magma which at first sight do not appear mutually consistent. Thus the degree of viscosity indicated by the presence of thinly tabular sheets of inclusions within the granite, standing nearly upright and unsupported except by the magma on either side, does not harmonize with the facility with which magmatic material has been transfused into the original rock. In trying to reconcile these features inquiry has been directed toward a consideration of certain of the properties of magmatic solutions. The question of the critical temperatures of volatile substances is discussed in its bearing upon their condition within the magma. Further, the problem of a possible differentiation of a magma when injected into a wall-rock in a multitude of adjacent streams is taken up, as related to the views expressed by the advocates of *lit-par-lit* injection. Several methods by which this might be accomplished appear possible, and it is suggested that the escape of gases from the magma into the wall-rock would have a tendency in this direction and that at the same time the deposition of magmatic minerals by contact of tongues of magma with the cooler walls would effect results of a similar nature. Thus the advance of the main body of magma would be preceded by that of a more dilute portion, which would be able to impregnate the wall-rock with facility and initiate processes of transformation and solution which the more concentrated body following would carry farther toward completion.

December, 1913